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Case studies on the dynamics of Pi3 geomagnetic and riometer pulsations during auroral activations

N. G. Kleimenova¹, O. V. Kozyreva¹, K. Kauristie², J. Manninen³, and A. Ranta³

¹Institute of the Earth Physics, Moscow 123995, Russia

²Finnish Meteorological Institute, Geophysical Research Division, P.O. Box 503, FIN-00101 Helsinki, Finland

³Oulu University, Sodankylä Geophysical Observatory, FIN-99600 Sodankylä, Finland

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Abstract. A sequence of three subsequent auroral activations (at 18:10, 19:48 and 20:00 UT) on 9 February 1997 is analysed. The brightenings of optical auroras were collocated with latitudinally localized bursts of pulsating riometer absorption and Pi3 geomagnetic pulsations. In two of the cases, the strongest westward directed electrojet currents and the footpoint of the upward directed field-aligned currents related to the auroral brightening were observed in the same region as the largest amplitude of the pulsations and their polarization changed. In the third case, field-aligned current signatures were present, but not so pronounced that their accurate location could not be defined. In all cases, the spectra of geomagnetic and absorption pulsations were similar. Based on ground-based observations alone, it is difficult to say whether the energetic particle precipitation (riometer absorption) was modulated by the geomagnetic pulsations or whether the geomagnetic pulsations were caused by varying ionospheric currents controlled by the precipitating particle intensity. However, the localized nature of both pulsations of the two different phenomena and their tight coupling with each other seem to support the latter option.

Key words. Ionosphere (Particle precipitation) – Magnetospheric physics (auroral phenomena; MHD waves and instabilities)

1 Introduction

The brightening and breakup of a preexisting stable arc, the abrupt negative deviation in the magnetic north (X) component, and the magnetic Pi2 pulsations ($T = 40 - 150$ s) are typical substorm expansion phase onset signatures in the ionosphere (Akasofu, 1964; Fukunishi, 1975). It is not yet exactly known which processes in the magnetosphere cause the initial brightening of the auroral arc. The magnetic signatures can be associated with the build up of the substorm

current wedge (SCW) (McPherron et al., 1973). Pi2 pulsations are a consequence of the shear Alfvén waves carrying the field-aligned currents (FACs) in the wedge, and the ionospheric part of the wedge (a strong westward current) causes the negative X -bay. Pi2 pulsations have been recognized to be a fundamental element in magnetospheric substorm morphology, since they can be observed in a wide range of latitudes and longitudes on the ground (Olson, 1999). However, during the substorm sequence, Pi3 type geomagnetic pulsations very often also occur with longer periods than Pi2. According to Saito (1978), the substorm associated Pi3 pulsations can be separated into two categories: the Ps6 type, with periods longer than 400–600 s and dominantly observed in the D -component, and the PiP type, with periods less than 400 s and amplitudes comparable in all three components of the field. The PiP periods are from 150 to 400 s, and the average amplitudes from several tens of nT to hundred nT (Raspopov et al., 1973; Kiselev and Raspopov, 1976). The onset of PiPs at the higher latitudes lags behind the onset at auroral zone latitudes, where PiPs can be accompanied by auroral intensity fluctuations in the similar period range. Nagano et al. (1981) show that high latitude Pi3s with periods longer than 400 s are more commonly observed than PiP type pulsations, and that the amplitudes of Pi3s are largest near the center of the westward auroral electrojet. According to Suzuki et al. (1981), the distributions of nightside Pi3 are similar to those of Pi2. Kleimenova et al. (1998) showed that in the auroral zone, Pi3 pulsations ($f \sim 1 - 3$ MHz) are very localized in latitude and closely related to the substorm intensification.

Numerous observations have indicated that substorm associated energetic particle precipitation (as measured by riometers) can have temporal variations with periods of 3–15 min, i.e. in the frequency range of Pi3 periods (Wedeken et al., 1979). Furthermore, it has been shown that in the auroral zone, the Pi2 pulsations are highly correlated with the pulsating component of the riometer data (Stuart et al., 1977; Heacock and Hornsucker, 1977; Haldoupis et al., 1982). Simultaneous observations of optical aurora and energetic par-

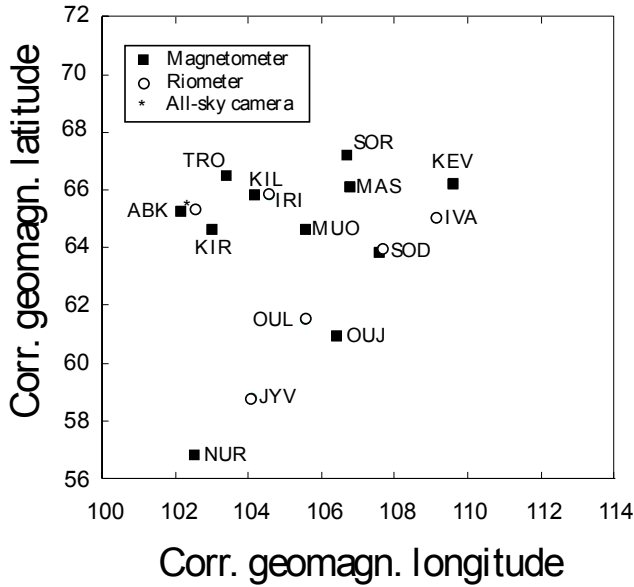


Fig. 1. A map showing the CGM latitudes and longitudes of the magnetometer and riometer stations.

ticle precipitation have been analysed in a few papers (Anderson and DeWitt, 1963; Barcus, 1965; Nielsen et al., 1988; Lazutin et al., 2000). The new point of this study is to analyse simultaneous observations of all three different types of phenomena. The behavior of auroral breakups, riometer absorption variations and Pi3 type pulsations during a sequence of several subsequent activations is investigated in order to demonstrate how these activations are spatially and temporally coupled with each other and with the other expansion phase phenomena.

2 Instrumentation

MIRACLE is a two-dimensional instrument network constructed for studies of mesoscale auroral activity in the Scandinavian sector (Syrjäso et al., 1998). The network includes 25 magnetometer stations (the IMAGE network, Lühr et al., 1998), eight all-sky cameras (ASC) and the STARE radar system with two coherent scatter radars. The sampling rate of IMAGE is 10 s. The ASCs acquire images through filters of 557.7 nm and 630.0 nm with the sampling rates of 20 s and 60 s, respectively. This study utilizes IMAGE data and ASC images recorded at Abisko (ABK, 68.36 N, 18.82 E). The field of view of the ABK ASC at the 100 km altitude is a circle with the radius of approximately 300 km. Spatial resolution of the ASC varies between less than a one km distance per pixel (near the zenith) to a few km per pixel (near horizon). Unfortunately STARE data are not available for the event analysed here. Combined with the MIRACLE data, we analyse recordings of a chain of 6 riometer stations: Ivalo (IVA, 30 MHz), one IRIS (Ionosphere Riometer Imaging System) beam (IRI, 38.2 MHz) (Browne et al., 1995), Sodankylä (SOD, 30 MHz), Oulu (OUL, 32.4 MHz),

and Jyväskylä (JYV, 32.4 MHz). The riometers measure the variation in the intensity of the galactic cosmic noise on the ground. The intensity of observed signal is a function of the height integrated electron density in the D- and E-regions, which, in the first instance, is a function of the energetic (more than 10–20 keV) electron precipitation. The sampling rate of the riometers is 10 s, and the beam covers at the 90 km altitude a circular area of 100 km diameter. Figure 1 shows the locations in corrected geomagnetic (CGM) coordinates of the instruments used in this study.

3 Observations

On 9 February 1997, the time between 12:00–24:00 UT was magnetically very disturbed. The quicklook AE index (based on the data of seven AE-observatories) shows at least four substorm-like activations, with peak AE values between 500 and 1800 nT around the hours of 14:00, 18:00, 20:00, and 22:00 UT. The WIND satellite was monitoring the solar wind at $X_{\text{GSM}} = 197 R_E$ ($Y_{\text{GSM}} = 8 R_E$, $Z_{\text{GSM}} = -16 R_E$). At 12:50 UT, the satellite observed a shock front with an abrupt increase in the ion density and earthward directed plasma velocity. The IMF direction was very variable until 16:20 UT, when IMF B_Z suddenly changed to strongly negative values (below -5 nT) and stayed there until 21:00 UT. The delay time from WIND to the Earth's magnetopause is approximately 35 min, if it is simply calculated using the measured solar wind velocity ($V_{\text{GSM}} = 560 - 600$ km/s) and the distance from the satellite to the Earth's magnetopause (at $X_{\text{GSM}} = 10 R_E$). Real observations seem to follow this approximation relatively well, since IMAGE recorded the sudden impulse (SI) driven by the solar wind shock at 13:21 UT.

Figure 2 (upper panel) shows the geographical location of the auroral electrojets as a function of time. The latitude profile of the X -component deviations recorded at the IMAGE middle meridian stations have been upward continued to the ionospheric level, using the method of Mersmann et al. (1979). In the upward continued latitude profiles, the electrojet boundaries are more pronounced than in the ground observed profiles. The latitudinal resolution of the method is $\sim 0.8^\circ$. The lower panel shows the estimated intensity of the electrojet current densities ($J = 2X/\mu_0$).

The data of Fig. 2 show growth phase activity, i.e. an intensification and equatorward shift of the auroral electrojets, starting at 17:00 and 18:30 UT. The effects of the expansion phase SCW currents are most clearly visible at the end of the growth phases, i.e. at 18:10 and 20:00 UT. At the ionospheric footprint of the upward field-aligned currents (FACs), there is a counterclockwise Hall current vortex. Consequently, on the poleward (equatorward) side of the footprint, westward (eastward) currents intensify. The vortices are seen as pairs of red and blue regions in the color plot of Fig. 2. Since only X -component data is used in the analysis, the plot does not show the effects of the poleward and equatorward currents that cause the deviations primarily in the magnetic east component below a vortex structure. In the latter case (after

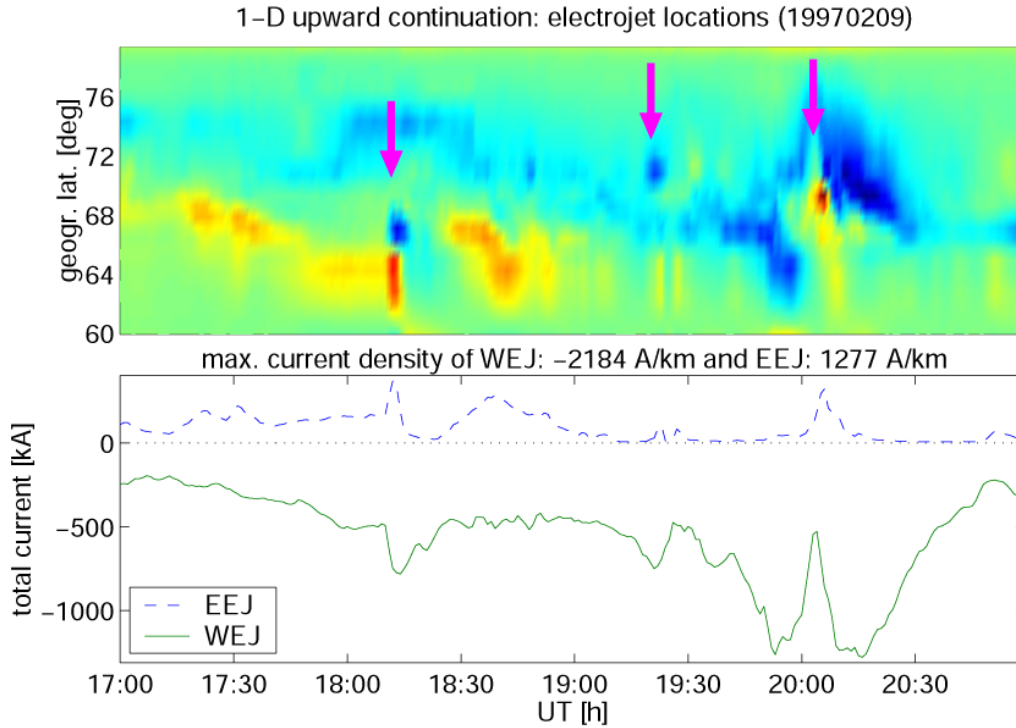


Fig. 2. The locations (in geographic latitudes) and intensities of the auroral electrojets as a function of time during the period of this study. In the top plot, the blue (red and yellow) colors show the location of the westward (eastward) electrojet (currents are close to zero in the green regions) and in the bottom plot, a solid (dashed) curve shows the total current intensity of the westward (eastward) electrojet.

20:00 UT), the vortex formed in a region previously dominated by the westward electrojet and thus a part of the eastward current is seen as “a hole in the westward currents”. Note that the plot also shows FAC-related signatures around 19:20 UT, although these signatures are not as clear at 18:10 and 20:00 UT.

A set of ABK ASC images is shown in Fig. 3. The ASC at ABK started to acquire images at 18:01 UT. The first images show dim auroral arcs in the zenith and somewhat brighter arcs both in the southern and northern horizons. The southern-most arc broke up at 18:10 UT and the activity spread rapidly from south to the zenith and later to the northern sky. Around 19:20 UT, the auroras in the southern horizon brightened again (not shown), but the activity stayed so close to the horizon that defining the exact dynamics was difficult. Around 19:48 UT, new bright auroras appeared to the zenith and a further intensification in the activity took place 19:52 UT, when a westward travelling surge (WTS) intruded from the eastern horizon to the zenith of the camera. The WTS related activity continued in the entire sky of ABK until 20:27 UT.

The auroral brightenings at 18:10 UT and from 19:48–19:52 UT can be associated both temporally and spatially with the clear SCW signatures of Fig. 2. In the first case, the breakup region was at the CGM latitude of 62.3° and in the second case it was at latitude 65° . According to Fig. 2, the footpoints of the corresponding upward directed FACs were at the CGM latitudes of 62.5° and 66.5° (the CGM lat-

itude is roughly 3.5° less than the geographical latitude in this region). The weaker FAC signature in Fig. 2 (19:20 UT) seems to be temporally related to the auroral brightening at 19:22 UT, but the spatial connection is not so clear; the auroras are clearly more south than the strongest magnetic signatures.

Figure 4 represents the magnetic X -component and riometer data: raw records (panel a), their dynamic spectra in the frequency range of 0.5–4.0 MHz (panel b) and 1–3 MHz filtered data (panel c), recorded at the IMAGE and riometer stations shown in Fig. 1. The magnetic Y -component of Pi3 pulsations is characterized by a little spectral difference. However, the space-time variations (not shown here) are similar to the X -component. The spatial distribution of 0.5–2.0 MHz geomagnetic pulsations is plotted in Fig. 5. Figure 6 demonstrates the integrated intensity of optical auroras in the approximate beam locations of the riometers IRI, IVA, and SOD.

The first auroral breakup caused magnetic effects primarily at the southern stations of SOD and OUI (Fig. 4, panel a, and Fig. 6). The breakup was accompanied by a short burst of riometer absorption observed at a very narrow latitudinal area (SOD) and in the Pi3 range pulsations both in the riometer and magnetometer data (Fig. 4). Both the riometer and magnetic pulsations have a maximum intensity at ~ 0.5 –2.0 MHz, were recorded simultaneously at the same latitudes, and were approximately in anti-phase (Fig. 4, panel c). In both spectra, there is also an amplitude enhancement in

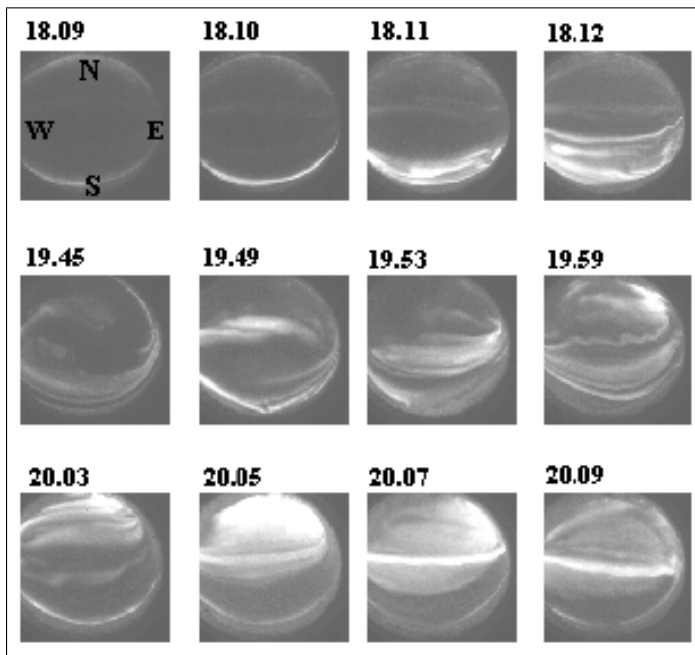


Fig. 3. ASC frames recorded at the station ABK around the times of the auroral intensifications (18:10 UT, 19:48 UT and 20:00 UT).

the PiP range (2–4 MHz). The phase of the PiP magnetic pulsations at SOD led the wave phase at OUJ for about one-third of the average wave period. The rotation of the polarization vector at these stations was the opposite: clockwise at higher latitudes (SOD) and counterclockwise at lower latitudes (OUJ), i.e. that the source of the wave is located between these stations. The 0.5–2.0 MHz (Pi3) pulsation shows the similar morphological properties and there is no reason to separate PiP and Pi3 into different types.

The top panel of Fig. 5 shows the map of the spatial distribution of Pi3 geomagnetic pulsation amplitude integrated for the time interval of 18:00–18:20 UT. The area of the maximum amplitude is marked with the gray shading. The map, together with Figs. 2 and 4, demonstrate that the strongest 0.5–2.0 MHz magnetic pulsations were recorded in the same region as the strongest riometer absorption, and this was the same region where the footpoint resided of the SCW related upward FAC resided and where the auroral breakup took place. More accurately, the footpoint of the FAC was between stations SOD and OUJ, which observed the pulsations with different phases. A very sharp attenuation of the Pi3 amplitude can be seen in Fig. 5 (top panel) near the CGM latitude of 65° . This boundary cannot be the polar cap boundary since auroras were also observed on its poleward side, but it can correspond to the tailward edge of the substorm activity region in the near-Earth magnetosphere (Baker et al., 1996).

The riometer absorption and Pi3 activity around 19:30 UT (Fig. 4) are most probably associated with the auroral and magnetic activations at 19:20 UT. It is interesting to note that the riometer pulsations (Fig. 4, panel b) are strongest in the southern region (SOD) where the auroras were strongest, while the magnetic signatures, pulsations and the FAC-signature in Fig. 2 dominated at higher latitudes (KEV).

The next period of strong pulsation and riometer activity started around 19:48 UT. The magnetometers in Fig. 4 (panel a) show that the negative deviation in X was at first the strongest at OUJ. The bay was accompanied by a burst of the pulsating riometer absorption and Pi3 geomagnetic pulsations. The middle panel of Fig. 5 shows the spatial distribution of Pi3 geomagnetic pulsations at 19:40–20:00 UT. During this period, the maximum of the Pi3 amplitude was located near OUJ, which is at lower latitudes than during the first breakup (18:11 UT). The rotation of the polarization vector of geomagnetic pulsation (both Pi3 and PiP range) changed between SOD and OUJ. At this time, contrary to the first breakup, the rotation was counterclockwise at higher latitudes (SOD) and clockwise at lower latitudes (OUJ). This would suggest that the upward FAC was between SOD and OUJ. In this case, the electrojet boundary plot of Fig. 2 does not provide further confirmation for this conclusion as it does for the first breakup (clear FAC signatures are visible only after 20:00 UT).

When the WTS moved above the zenith of ABK around 20:00 UT the riometer and magnetic activity also shifted to higher latitudes. The most intensive aurora was observed at $\sim 20:05$ UT, northward of ABK, and the center of the westward electrojet shifted to the CGM latitudes of 66 – 67° (Fig. 2). The strongest riometer absorption, and riometer and magnetic pulsations (both PiP and Pi3) were observed at the same latitudes. The direction of the vector polarization of Pi3 pulsation was clockwise near KEV, and the Pi3 polarization reversal occurred between KEV (CGM latitude of $\sim 66^\circ$) and SOD (CGM latitude of $\sim 64^\circ$), which is somewhat south of the FAC footpoint (CGM lat 66.5°) as suggested by the plot in Fig. 2. The spatial magnetic-Pi3 distribution for the period of 20:00–20:20 UT is shown in the bottom panel of Fig. 5.

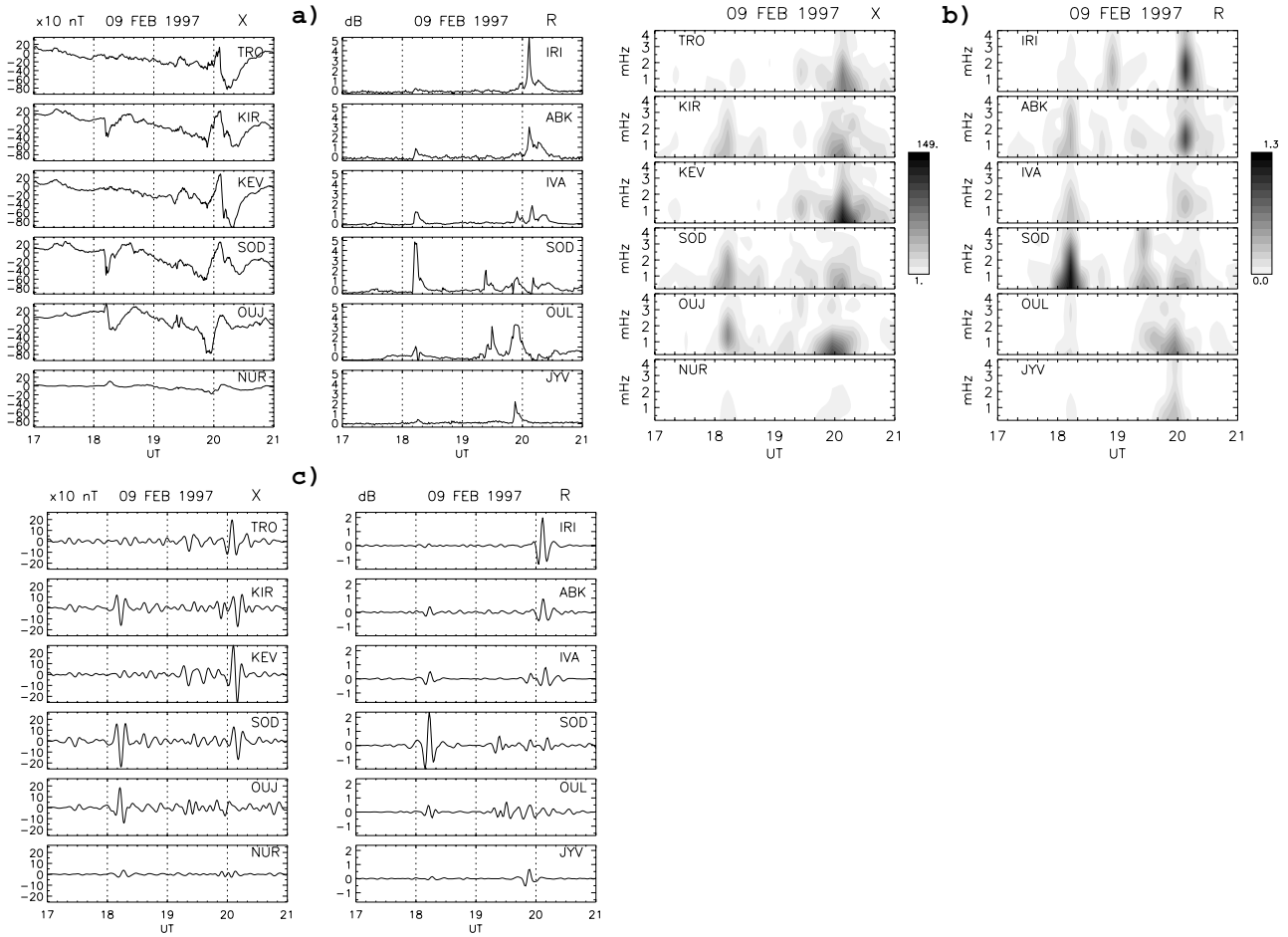


Fig. 4. The magnetic X-component and riometer data: raw records (panel a), their dynamic spectra in the frequency range of 0.5–4.0 MHz (panel b) and 1–3 MHz filtered data (panel c), recorded at the IMAGE and riometer stations shown in Fig. 1.

The plot shows a sharp border at the CGM latitude of 65° , equatorward of where the activity attenuates significantly.

4 Discussion

The activity discussed in this study can be related to the magnetospheric processes in the near-Earth region ($X_{\text{GSM}} \sim -6 \dots -10 R_E$). The magnetospheric origin of expansion phase onset arcs is known to be within the central plasma sheet (Feldstein and Galperin, 1985; Birn and Hesse, 1998), or more accurately, at the inner border of the central plasma sheet near the region of dipolarization (Ranta et al., 1977). On the other hand magnetic reconnection, which is most likely the original energy source of the expansion phase activity, takes place in the mid-tail region ($X_{\text{GSM}} \sim 20 R_E$). Consequently, variations in the reconnection process cannot directly cause the modulations in the energetic precipitation or in the magnetic pulsations. Nevertheless, reconnection can indirectly control the appearance of the pulsations, since it causes fast earthward directed plasma flows, FACs, and the dipolarization of the geomagnetic field on the earthward side of the reconnection region. FACs cause pulsations primarily

in the Pi2 range, but the breaking of the earthward directed flows in the region of quasi-dipolar field lines (Shiokawa et al., 1997) may cause lower frequency hydromagnetic waves, which can modulate the intensity of energetic particle precipitation. Nevertheless, such interaction processes are likely to cause global effects, while our observations show a poor correlation between geomagnetic observations at stations whose separations are clearly less than the Pi3 wavelengths.

Breakup arcs have been shown to have their magnetospheric origin adjacent to the energetic (30–80 keV) electron isotropic boundary (Lui and Burrows, 1978; Elphinstone et al., 1996). This means that under average conditions, energetic electrons should be trapped equatorward of the breakup arc. During the growth phase, however, the riometer absorption usually increases in the breakup region (Pytte et al., 1976; Ranta et al., 1981). Consequently, in the corresponding magnetospheric region, some non-linear processes, probably related to the stretching of field lines to a more tail-like configuration, cause a randomisation in the motion of energetic electrons. For example, the cyclotron instability of trapped energetic electrons modulated by a ULF wave could cause similar oscillations in the riometer absorption, as observed in

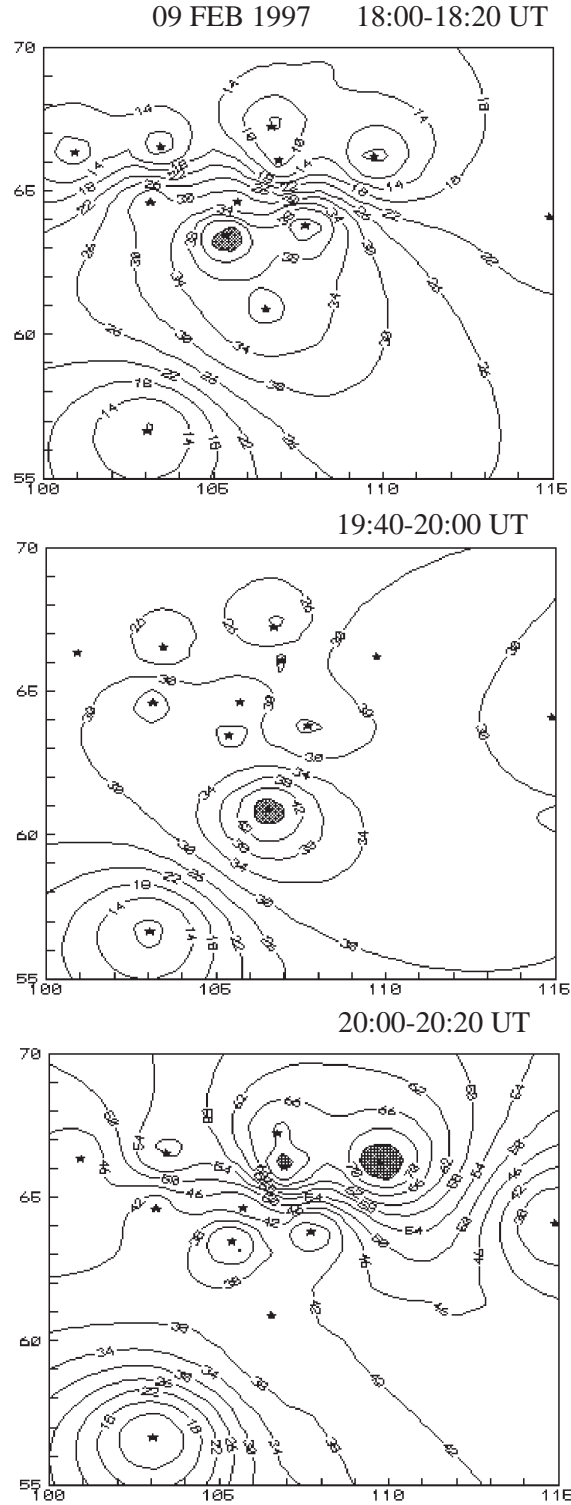


Fig. 5. The spatial distribution of the 0.6–2.0 MHz magnetic pulsations in CGM coordinates; asterisks show the station locations.

this study. The magnetospheric inductive electric field has also been suggested to cause variations in the energetic and soft auroral precipitation (Kauristie et al., 1995). In this scenario, the inductive electric field would disturb the energization process of the cross-tail curvature drifting particles that

gain energy from the convection electric field (Pellinen and Heikkilä, 1978, 1984). However, this model predicts a single fading of the precipitation prior to the onset rather than a sequence of pulsations.

Optical auroral arcs are caused by soft electron precipita-

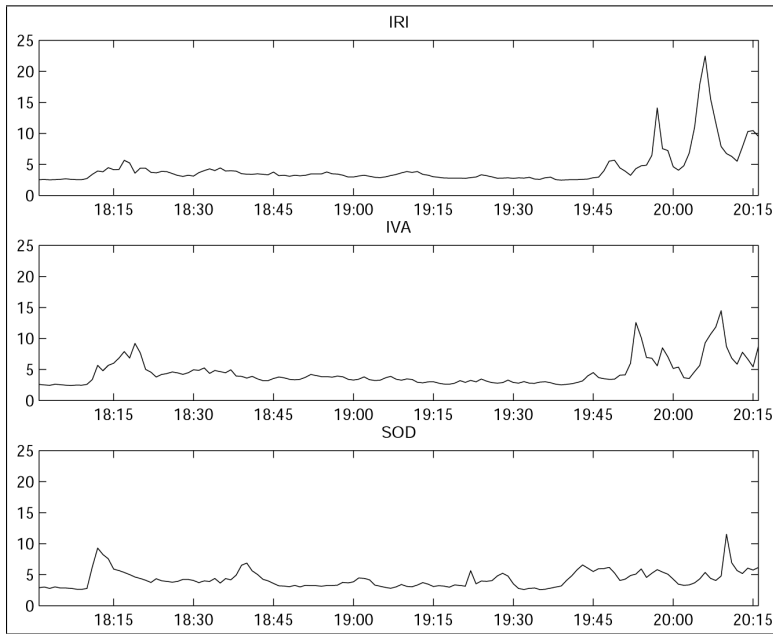


Fig. 6. The integrated intensity of optical auroras (in arbitrary units) as a function of UT in the regions of the riometer beams at IRI, IVA, and SOD.

tion with very discrete and localized structure (Weimer et al., 1994). Auroral precipitation and the related FACs can oscillate in the frequency range of 1–4 MHz (Samson et al., 1996). Moreover, numerous observations (Wedeken et al., 1979) have indicated that substorm associated injections of energetic particle precipitation can have variations with periods of 3–15 min. The oscillations of particle precipitation associated with fluctuating upward FACs can enhance the conductivity of the ionosphere and cause periodic variations in ionospheric currents, which are observed as ground magnetic pulsations in the same frequency range. The fluctuations in the ionospheric electrojets caused by fluctuating FACs as a source of irregular geomagnetic pulsations have been discussed, (by, e.g. Wilhelm et al., 1977; Nagano et al., 1981; Suzuki et al., 1981). Kleimenova et al. (1998) showed that during the evening-nighttime, the high latitude Pi3 pulsations are typically very localized in latitude and closely associated with the substorm intensification. We observed these pulsations in the magnetic field and in the energetic precipitation, but their existence in the optical aurora remains without confirmation, since the other time variations in the auroral activity efficiently shield the probable pulsation-type variations.

Paquette et al. (1994) studied simultaneous riometer and magnetic pulsation events that took place during the daytime. They tested the hypothesis suggested by Coroniti and Kennel (1970) which associates the coupled magnetic and precipitation pulsations with the ULF modulation of VLF wave-particle interactions that take place at the magnetospheric equator. In this scenario, a ground-based observer in an appropriate location would observe significantly the onset of riometer pulsations before the magnetic pulsations since the electron propagation time from the source region to the ionosphere is much shorter than the Alfvén transit time. Roughly one-third of the events of Paquette et al. were consistent with

the theory of Coroniti and Kennel. In one-third of the cases, the magnetic pulsations were observed before the precipitation pulsations, which was most likely due to the localized nature of the riometer observations when compared to the magnetic field measurements. In the remaining third of the events, the onsets of riometer and magnetic pulsations were simultaneous. A natural way to explain such behaviour is to assume that the fluctuations in the particle precipitation modulated the ionospheric conductivity and currents, and thus caused the magnetic pulsations (Heacock and Hornsucker, 1977; Rosenberg et al., 1981; Haldoupis et al., 1982). In none of our events did the onset of riometer pulsations precede the magnetic pulsations. Thus, these events do not provide clear support for the theory of Coroniti and Kennel. At the auroral breakup on 18:10 UT, the onsets of the two types of pulsations were simultaneous, which suggests that the scenario of modulating ionospheric currents would be more valid, at least for this specific case.

Profound evidence of magnetic Pi3-pulsations, generated by modulating ionospheric currents, is presented in the study of Haldoupis et al. (1982), where riometer and magnetic recordings are analysed together with the data of the STARE VHF-radar. In the radar data, pulsations with a similar frequency ($T \sim 3$ –4 min) as in the magnetic and riometer data can be seen in the backscatter intensity (which is proportional to the electron density), but not in the electric field. The authors associate the magnetic variations with ionospheric Hall-currents which vary due to the precipitation fluctuations. In their case, the pulsations in the riometer and magnetic X-component were in phase, while in the events analysed, here the two types of pulsations were both in phase and anti-phase: at 18:10 UT, the absorption pulsations were strongest at SOD and they were in anti-phase with the magnetic pulsations at the same station (Fig. 4, panel c), while

after 20:00 UT, the absorption pulsations recorded at IRI were in phase with the TRO magnetic pulsations. Similar to the study of Haldoupis et al., the magnetic pulsations can be associated with Hall-currents and especially associated with the Hall-current vortices at the footpoints of the upward enhancing FACs at the auroral breakups. At 18:10 UT, SOD (OUJ) was northward (southward) of the FAC footpoint and thus the enhancements in the precipitation (corresponding positive dB-values in Fig. 4, panel c) and in Hall-currents caused negative (positive) deviations in the X -component and consequently, the riometer and X -pulsations were in anti-phase (phase). After 20:00 UT, the magnetometer stations TRO, KIR, KEV were southward of the FAC footpoint and consequently, the enhancement in the Hall-current caused positive X -deviations at these stations (Fig. 4, panel a). The systematics in the pulsations, however, are not clear, e.g. the riometer pulsations recorded at IVA are in anti-phase with the X -pulsations recorded at the nearby stations KEV. Unfortunately, STARE data are not available for this day and thus we cannot check whether electric field variations could explain the non-systematic behaviour.

The magnetospheric mechanism which generates the pulsations in the energetic precipitation still remains an open question. In the model of Coroniti and Kennel (1970) for dayside activity, the basic mechanism that causes particle precipitation is the VLF wave-particle interaction process at the magnetospheric equator. In the nightside, the particle precipitation is also controlled by the substorm related changes in the magnetic field configuration. When the magnetotail stretches, for example, during the substorm growth phase, particle trajectories become randomised near the equatorial plane which causes precipitation. According to the present understanding, substorms can be associated with activity in two different regions: The current disruption region in the near-Earth tail and the reconnection region in the mid-tail (Baker et al., 1996; Lui, 1978). The observations analysed in this study were made in the conjugate region of the near-Earth magnetosphere and thus it is reasonable to assume that the Pi3 pulsations were related to the current disruption process.

The mechanisms of acceleration of the breakup associated with soft precipitation and energetic precipitation are different. Acceleration region processes at an $\sim 1\text{--}2 R_E$ altitude control the distribution of soft auroral precipitation while the processes near the magnetospheric equatorial plane control the appearance of energetic precipitation. The examples analysed in this study, as well as the events analysed by Lazutin et al. (2000), demonstrate that the most intensive auroral brightenings and injections of energetic precipitation are coupled both spatially and temporally. The observations give the impression as if the injections of energetic particle precipitation would catalyse the build-up of field-aligned potential and create a drop in the acceleration region. Understanding of the interaction process between these two separate magnetospheric regions is a challenging issue for future studies.

5 Summary and conclusions

Based on our observations, we can conclude that:

- Substorm related bursts of Pi3 geomagnetic pulsations are very localized on the ground. and they coincided with the bursts of riometer absorption. The spectra of riometer and geomagnetic pulsations are similar;
- Pi3 pulsations (magnetic and riometer) are spatially and temporally coupled with auroral breakups and upward directed field-aligned currents;
- In one of our breakup events, the onsets of riometer and magnetic pulsations were simultaneous which leans towards supporting the theory that relates magnetic pulsations to ionospheric conductivity modulations rather than the theory that suggests a common magnetospheric source region for both riometer and magnetic pulsations.

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